

Article

A Numerical Study of the Effect of Water Speed on the Melting Process of Phase Change Materials Inside a Vertical Cylindrical Container

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Abstract: The present work offers a thorough analysis of the impact of water velocity on phase change material (PCM) melting in a vertical cylindrical container. A detailed quantitative analysis uses sophisticated numerical techniques, namely the ANSYS/FLUENT 16 program, to clarify the complex relationship between enthalpy and porosity during the melting process. The experimental focus is on phase transition materials based on paraffin wax, particularly Rubitherm RT42. This study's primary goal is to evaluate the effects of different water velocities (that is, at velocities of 0.01 m/s, 0.1 m/s, and 1 m/s) on the PCM's melting behavior at a constant temperature of 333 K. This work intends to make a substantial contribution to the development of thermal energy storage systems by investigating new perspectives on PCM behavior under various flow circumstances. The study's key findings highlight the possible ramifications for improving PCM-based thermal energy storage devices by revealing significant differences in melting rates and behavior that correlate to changes in water velocities. Future research is recommended to explore the impact of temperature variations, container geometries, and experimental validation to improve the accuracy and practicality of the results and to advance the creation of sustainable and effective energy storage solutions.

Keywords: phase change material (PCM); melting process; heat transfer; thermal energy storage; velocity effect



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1. Introduction

Solar energy is strongly tied to human everyday life and substantially influences modern civilization's development, which depends on several critical industries. Most people know that specific energy sources ultimately run out and others have negative environmental repercussions. As a consequence, researchers across the globe are working to develop substitute renewable energy sources. The fact that renewable energy is long-term, affordable, and ecologically reasonable is only one of its many advantages. It has the potential to be utilized everywhere, but the lack of regular access to sources like wind and sunshine is its major constraint [1–3]. One method to deal with this is by storing thermal energy. PCMs are the primary materials used in thermal energy storage [4–6]. Many experiments have been conducted on various forms composed of phase changing materials and the impact that shape has on a material's thermal energy storage capacity. Studies on methods to enhance heat transmission show that copper rods are the most successful. Many studies have demonstrated the benefit of using numerical projections in

experiments [7–10]. The melting of PCMs is sped up with every degree that the temperature of the air being introduced increases, and the energy charge for both sensible and latent PCM heat increases considerably [11–13]. The PCM melting process in a rectangular container was numerically and experimentally analyzed by Rizan et al. [14]. According to the study's findings, the melting process accelerated with every increase in heat flow. A computational investigation on the possibility of PCM-filled cylindrical cells acting as thermal energy storage devices was conducted by Ismail et al. [15]. Because of the PCMs' very high temperature in the center of the PCM cylinder, the cylinders in the first cell of the column melted more quickly than those in the cells that followed it in the column. Experimental research presented by Sattari et al. [16] focused on the PCM melting process in a spherical cell. According to the study, the melting process decreased as cell lead width increased. An experimental examination of shell and tube latent heat storage for solar dryers conducted by Agarwal and Sarviya [17] used paraffin wax as the heat storage medium. According to the research, the impact of natural convection was less significant in the bottom half of the region spectrum than in the top region. Natural convection is the primary mechanism for heat transmission, and melting occurs more quickly near the top owing to the buoyant effect [18]. The PCM's multi-tube melting process was analyzed by Izadi et al. [19]. According to the research, melting progress sped up as temperature and tube count rose. Esapour et al. [20] conducted research on how PCMs melt in a shell and tube configuration. The research demonstrated that the melting process had distinct effects on heat tubes. Increasing the inner HTF tubes caused an acceleration in the melting process, and enhanced heat transport with the addition of the nanoparticle was experimentally tested. Several studies have demonstrated that adding nanoparticles to PCM improves heat transport, shortening the time for the melting process to complete [21,22]. Other studies conducted experiments in which nanofluids were added to PCMs as a new phase to investigate their effect on a material's capacity for thermal energy storage [23,24]. The studies' findings indicated that the addition of nanofluid to PCM improved thermal conductivity, leading to a decrease in the time needed for the melting process. This study explores the effects of water velocity on the melting of PCM in vertical cylindrical containers for thermal energy storage systems. The investigation was conducted using advanced numerical models. The study examines the behavior of a phase transition paraffin wax-based material, Rubitherm RT42, under different flow conditions, providing new insights into the underlying processes that govern PCM behavior. These findings are essential for improving PCM-based thermal energy storage systems, which are important for developing the sustainable and efficient energy storage solutions needed to tackle current energy concerns and speed up the shift towards renewable energy sources. This research provides valuable insights into the complex relationship between fluid dynamics and phase change processes, specifically regarding the effects of adding nanofluid to PCM properties. This knowledge contributes to advancements in energy storage technologies and supports the development of resilient and sustainable energy systems.

2. Phase Change Material (PCM)

This study delves into a comprehensive examination of the properties and characteristics of Rubitherm RT42, a specific type of PCM. Table 1 provides a concise summary of the thermophysical parameters of the material that were the subject of this inquiry. This study attempts to clarify the details of Rubitherm RT42 by means of numerical analysis, illuminating its thermal behavior and important characteristics associated with its use in different thermal energy storage systems. The goal of the study is to provide important insights into the appropriateness and performance of Rubitherm RT42 as a PCM by methodically assessing its thermophysical parameters, as listed in Table 1. This will help with the design and optimization of thermal energy storage systems.

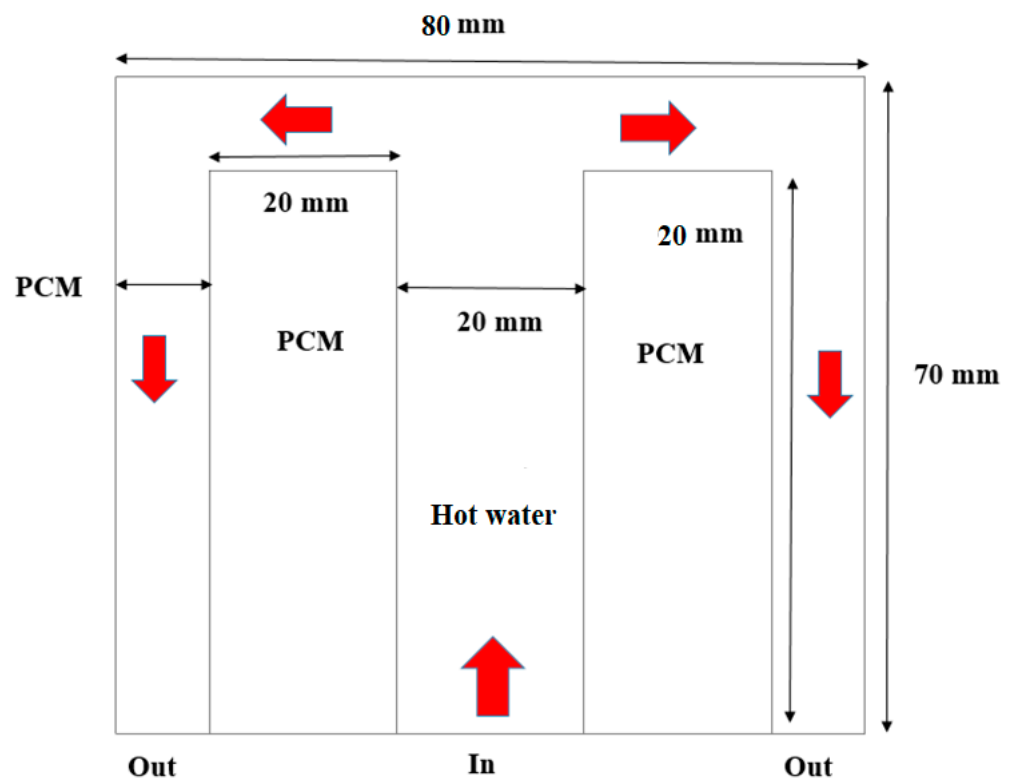
Table 1. The thermophysical properties of Rubitherm RT42.

Property	Value	Units
Density (liquid, solid), ρ	760	kg/m ³
Specific heat capacity, C_p	2000	J/(kg·K)
Thermal conductivity, k	0.2	W/(m·K)
Latent heat L	165,000	J/kg
Dynamic viscosity, μ	0.02351	kg/(m·s)
Thermal expansion coefficient	0.0005	1/K
Solid temperature	311	K
Liquid temperature	315	K

3. Method

3.1. Physical Modeling

The physical prototype used in this study is a cylinder that is positioned vertically and has a diameter of 80 mm. It is completely insulated to prevent any loss of heat. This structure contains two vertical cylinders, each having a diameter of 20 mm. The smaller cylinders are thermally insulated at their bottoms, while the other three sides are directly exposed to the heat source. Hot water is introduced into the core area of the cylinder through a 20 mm diameter opening and escapes through the side area via a 10 mm diameter opening. This structure enables the vertical cylinder to be exposed to the heat source from three sides, helped by the flow of water. Figure 1 illustrates the physical model used in this study. This inquiry focuses on examining the impact of hot water velocity on the process of melting. For this purpose, three different velocity situations were analyzed: 0.01 m/s, 0.1 m/s, and 1 m/s. The temperature of the experimental setup was kept constant at 333 K.

**Figure 1.** Configuration of a physical model explaining the dimensions and the HTF flow direction.

3.2. Computational Procedure

A numerical analysis performed inside the cylindrical container acted as a prognostic tool for comprehending the process of melting. The examination revealed that the flow

inside the container cannot be compressed, has smooth and orderly properties, and is limited to a flat, two-dimensional area. In order to effectively depict the melting process, it is crucial to assume that both the solid and liquid phases are isotropic and homogenous, ensuring that the temperature remains consistent at the interface. The work utilized the enthalpy–porosity technique to simulate the phase change region in the PCM. Nevertheless, it is important to acknowledge that the PCM melting process is fundamentally intricate, marked by nonlinearity, temporal variation, and the continuous movement of the liquid–solid interface. The governing partial differential equations for PCM melting, specifically the continuity, momentum, and energy equations, are formally expressed as Equations (1)–(3), as documented in earlier literature [25–28]. These equations are fundamental for comprehending the dynamic interaction between thermal and fluid dynamics processes in the PCM domain during the process of melting.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \quad (1)$$

$$\frac{\partial (\rho \mathbf{V})}{\partial t} + \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla P + \mu \nabla^2 \mathbf{V} + \rho \mathbf{g} + \mathbf{S} \quad (2)$$

$$\frac{\partial}{\partial t} (\rho H) + \nabla \cdot (\rho \mathbf{V} H) = \nabla \cdot (\mathbf{K} \nabla T) \quad (3)$$

The total of the sensible enthalpy (h) and the latent heat (ΔH) is the specific enthalpy (H).

$$H = h + \Delta H \quad (4)$$

$$h = h_{\text{ref}} + \int_{T_{\text{ref}}}^T C_p dT \quad (5)$$

$$\nabla H = \beta L_f \quad (6)$$

The meaning of the latent heat ability varies between zero (for a solid) and one (for a liquid). The liquid fraction (β) can be conveyed as follows, with the latent heat ability ranging from zero for a solid to one for a liquid:

$$\beta = \begin{cases} 0 & \text{solidus if } T < T_s \\ 1 & \text{liquidus if } T > T_l \\ \frac{T - T_s}{T_l - T_s} & \text{if } T_s \leq T \leq T_l \end{cases} \quad (7)$$

The source term S in the momentum equation is Darcy's law damping term added to the momentum equation due to the phase change effect on the convection. The source term in the momentum equation is given by:

$$S = \frac{C(1 - \beta)^2}{\beta^3} \mathbf{V} \quad (8)$$

The coefficient (C) is a mushy zone constant, reflecting the melting forefront's morphology. This fixed is a considerable number, usually (10^4 to 10^7). In the current study, (C) was assumed constant and was set to (10^5) [29].

3.3. Grid Independence and the Code Validation

The first stage of computational fluid dynamics (CFD) research, called the grid independence study, is crucial because it assesses the impact of different mesh densities on phase transition events in a certain geometric arrangement. Quadrilateral elements are used to generate the mesh for heat transfer simulations, since this model is a better choice to improve the accuracy and enhance the heat transfer representation. The primary objective of this experiment was to observe the progression of phase change events taking place inside the heat transfer fluid (HTF) under a consistent input flow rate of 1 m/s. Three different

mesh densities, with element counts of 22,701, 24,032, and 26,088, were carefully selected to cover a range of computational resolutions, as shown in Figure 2. After conducting a thorough analysis of the complete grid ensemble, it was determined that the sequence of phase transition remained uniform across all element numbers. This observation demonstrates grid independence, indicating that the calculated results were not significantly affected by the choice of mesh density. The mesh with the lowest element count (22,701) was carefully chosen for subsequent simulations since it had a faster computing time. This choice ensured that computational efficiency was maximized while maintaining accuracy standards. This methodological approach improved the dependability of the computational results and emphasizes the importance of careful grid selection in CFD calculations.

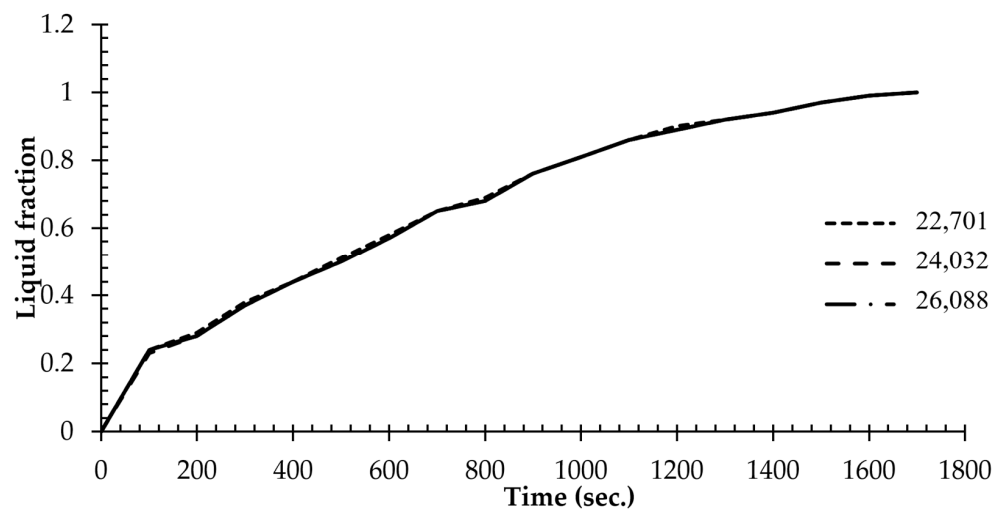


Figure 2. Grid independency test velocity = 1 m/s.

The liquid fraction is calculated during the simulation using Equation (7), which is applied in each step or iteration of the process. Initially set to zero at the beginning of the simulation, the liquid fraction progressively increases as time advances. This increase signifies the transition of the PCM from a solid to a liquid state. As more heat is absorbed and the PCM reaches its melting point, the liquid fraction approaches and eventually reaches 1, indicating that the PCM has wholly melted and transformed into a liquid state. A rigorous validation method was rigorously carried out to enhance the trustworthiness of the numerical simulation framework. The simulation code was enhanced with additional features, allowing for the simulation of complicated geometric structures and varying liquid amounts. These improvements were made to synchronize the computational framework with the influential research conducted by Bechiri and Mansouri [11], which examined the intricacies of fluid flow and heat transport during the phase transition of a PCM in a vertical cylindrical tube. After conducting a thorough comparison analysis, the results produced by the improved simulation code were compared with Bechiri and Mansouri's findings. This comparison showed a significant agreement between the two datasets, as shown in Figure 3. The comparison between the slightly different computing methodologies and model settings showed very small differences, which highlights the correctness and strength of the improved simulation code. Interestingly, the enhanced simulation code was able to achieve a full phase change in just 28 h, which is a shorter duration than the 24 h in Bechiri and Mansouri's work. However, there was a remarkable similarity in the progression of liquid percentage between the two studies. The liquid portion reached an impressive 98% within 24 h in both Bechiri and Mansouri's study and the current simulation, highlighting the accuracy and dependability of the improved numerical framework in accurately representing the complex dynamics of phase transition processes. The validation method served to enhance the credibility of the computational findings and showcases the simulation code's competence in properly replicating real-world occurrences.

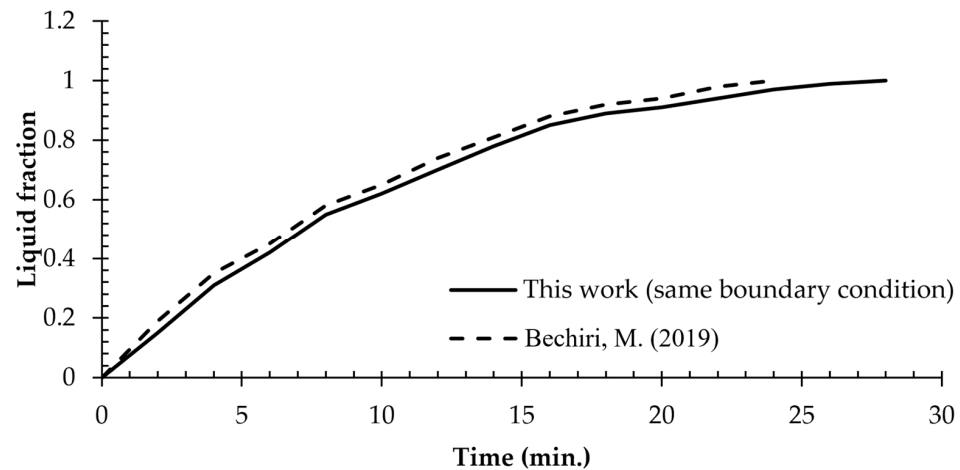


Figure 3. Distinction of the melting fraction versus operating time for this study against the work by Bechiri and Mansouri [11].

4. Results and Discussion

Figure 4 illustrates how the liquid fraction changed over time at different velocities of the heat transfer fluid (HTF) at certain time intervals (100, 600, and 1200 s). At first, regardless of the heat transfer fluid's velocity, the melting process's beginning was seen around the domain's boundaries. During the first 100 s, the phase change material (PCM) stayed mostly solid, except for a thin layer near the walls where melting began. Significantly, when the velocity of the heat transfer fluid (HTF) was 0.01 m/s, there was a progressive increase in the size of the liquid phase while the solid phase decreased accordingly. The upward movement of the liquid PCM within the domain was observed, which can be explained by the differences in density between the solid and liquid phases. The direction of molten PCM flow was primarily influenced by convective currents within the PCM domain, driven by factors such as buoyancy forces, thermal gradients, and mixing effects rather than strictly by density differences. When fresh liquid PCM moves upward to a fixed space, the species moving downward could be denser, cooler liquid PCM that sinks due to its lower temperature. The density of solid PCM impacts the flow of liquid PCM because as solid PCM melts, it creates density variations that lead to natural convection. Less dense liquid PCM rises due to increased temperature, while denser, cooler liquid sinks, resulting in intricate flow patterns within the domain.

Additionally, an interaction between heat transmission and fluid dynamics characterizes PCM melting. Heat initially transfers from the source via the solid PCM, causing a thin layer near the hot surface to melt. Melting leads to density variations, initiating natural convection. Understanding this complex relationship between thermal and fluidic processes is crucial for enhancing PCM performance in various applications.

After 1200 s, a significant amount of the PCM had melted, accounting for approximately 83% of the overall mass. The remaining solid phase (17%) was mainly located at the bottom of the area. An observable pattern arose where a rise in heat transfer fluid (HTF) speed was linked to a faster melting process. This can be attributed to increased heat transfer between the phase change material (PCM) and the HTF. Furthermore, at the 1200 s point, there was a noticeable decrease in the remaining solid material, which became more apparent as the velocity of the HTF increased. This occurrence shows the importance of HTF velocity in affecting the speed of phase transition within a system. Higher velocities lead to faster melting rates and a decrease in the remaining solid phase. These data highlight the complex relationship between fluid dynamics, heat transfer processes, and phase change kinetics, providing a clearer understanding of the mechanisms that drive the observed patterns.

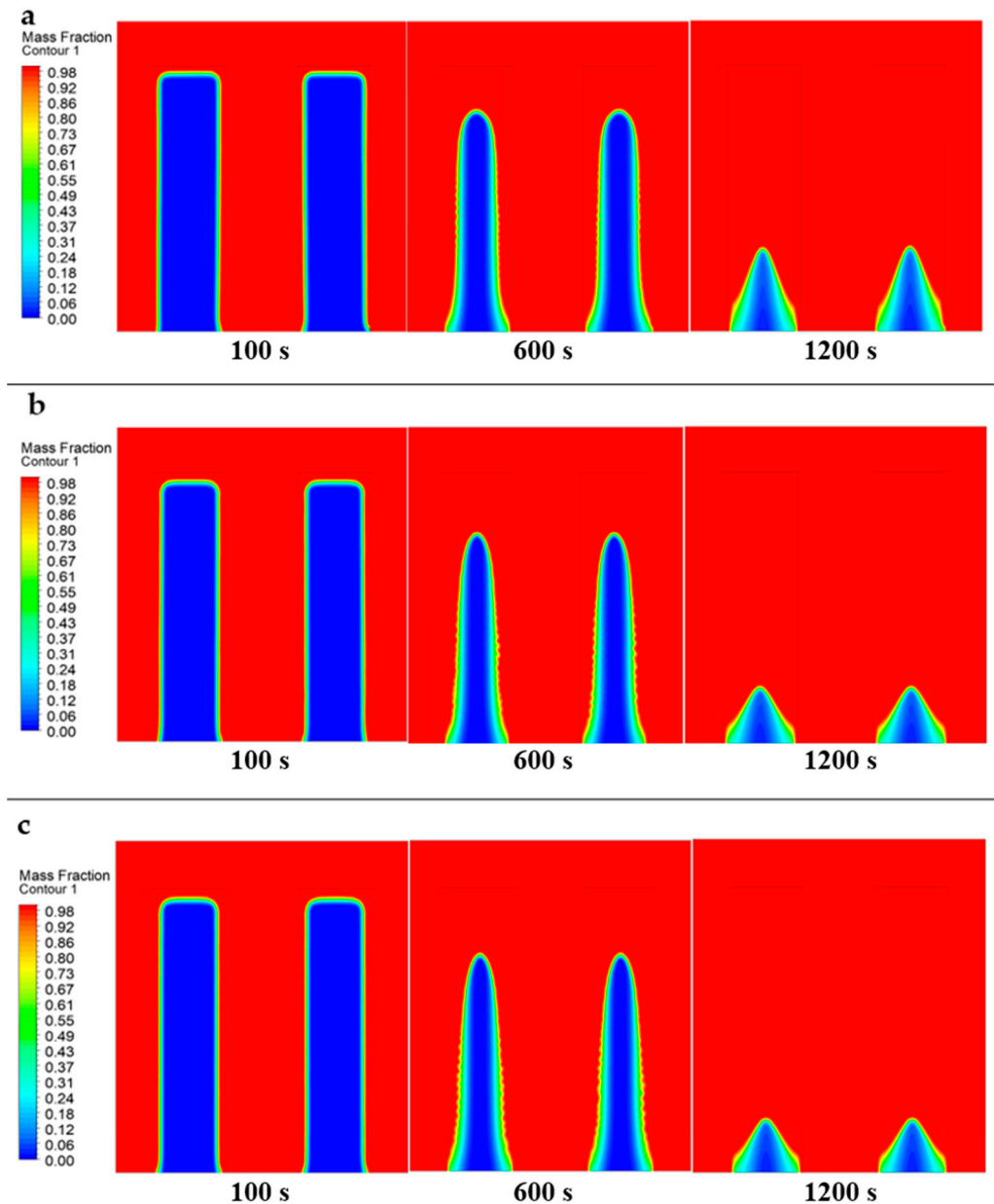


Figure 4. Predicted evolution of the melting process at various velocities: (a) 0.01 m/s, (b) 0.1 m/s, and (c) 1 m/s.

Figure 5 illustrates the temperature distribution contours at different velocities of the heat transfer fluid (HTF) for specific time intervals (100, 600, and 1200 s). Initially, the temperature increased along the walls in each HTF velocity scenario due to heat absorption. During the first 100 s, the entire phase change material (PCM) maintained a relatively low temperature of 310.18 K, except for a narrow area along the walls where heat transfer occurred. At an HTF velocity of 0.01 m/s, heat gradually spread throughout the PCM, causing an increase in temperature in specific areas, particularly the liquid phase zone. Moreover, the areas with higher temperatures in the phase change material (PCM) tended to gather towards the upper part of the region, driven by differences in density between the solid and liquid phases of the PCM. At the 1200 s mark, the average temperature of the PCM hit 328 K. The highest regions of the domain recorded temperatures as high as 332 K, while the bottom sections remained at 310.18 K. An observable pattern arose where the rate of temperature increase intensified as the velocities of the heat transfer fluid (HTF)

increased due to enhanced heat exchange between the phase change material (PCM) and the HTF.

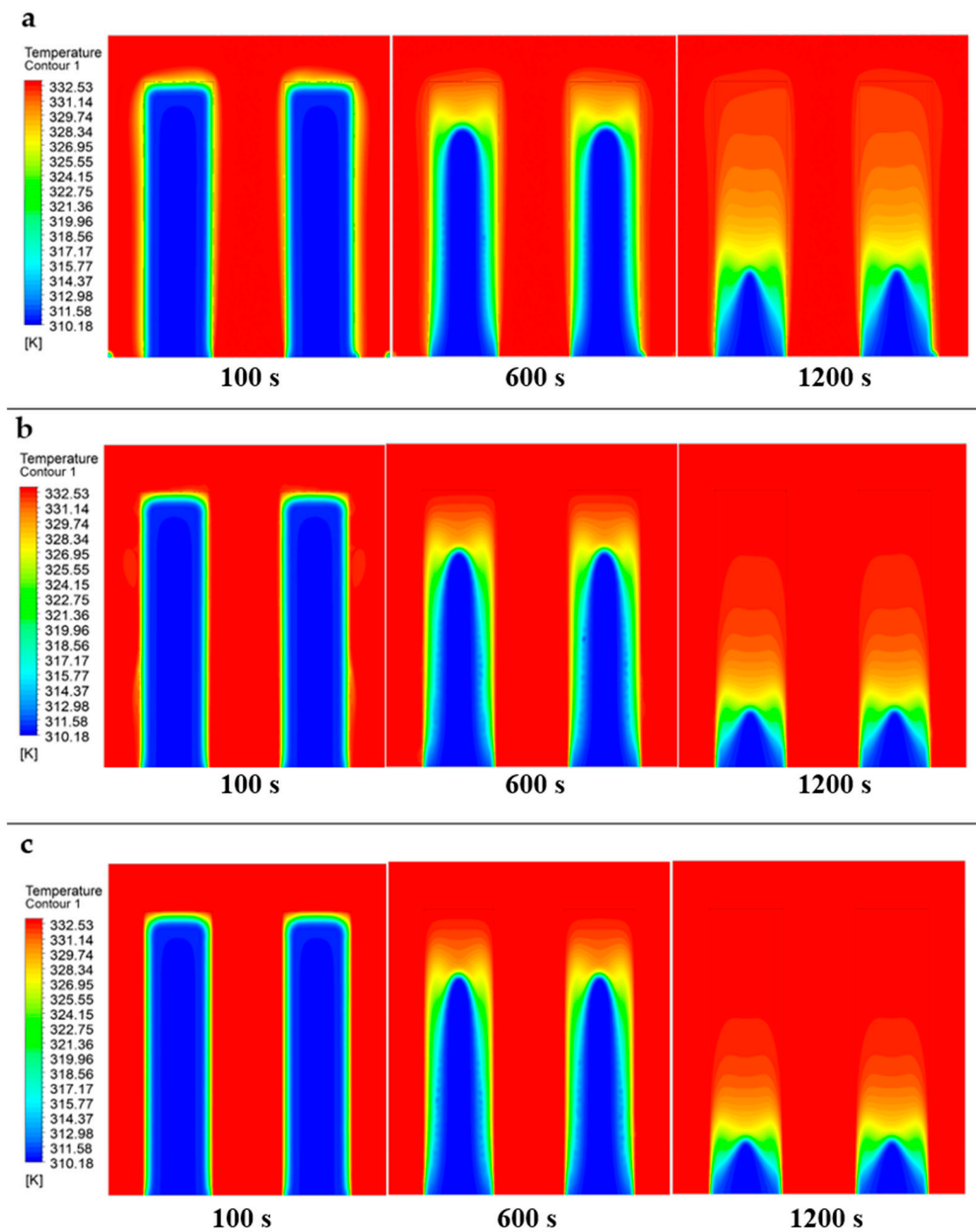


Figure 5. Temperature distributions of the PCM domains at various velocities: (a) 0.01 m/s, (b) 0.1 m/s, and (c) 1 m/s.

Furthermore, after 1200 s, a noticeable increase in the average PCM temperature was observed as the HTF velocities increased, with temperatures reaching 329 K and 331 K at HTF velocities of 0.1 m/s and 1 m/s, respectively. These data emphasize the significant impact of HTF velocity on the dynamics of temperature distribution within a system. They illustrate the crucial role of heat transfer mechanisms in forming thermal profiles and emphasize the consequential effect on phase change kinetics within the PCM domain. Figure 6 presents a detailed representation of velocity distributions within the phase change material (PCM) domains at different velocities: (a) 0.01 m/s, (b) 0.1 m/s, and (c) 1 m/s. The molten phase change material (PCM) speed was closely connected to the speed of the system's heat transfer fluid (HTF). This relationship is emphasized by the improvement of

convective heat transfer at higher HTF speeds, which affected the heat transfer rate during the melting process.

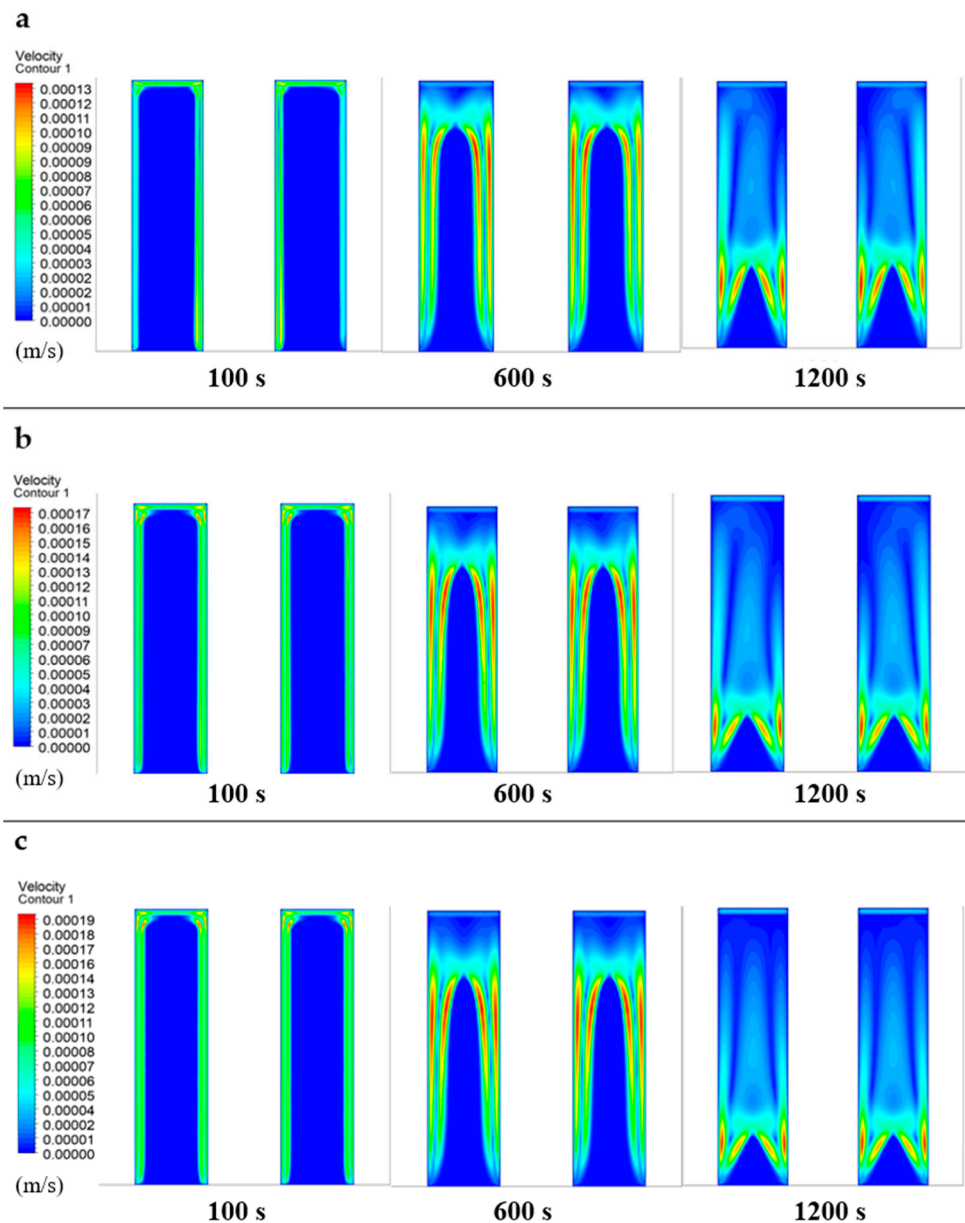


Figure 6. Velocity distributions in the PCM domains at various velocities: (a) 0.01 m/s, (b) 0.1 m/s, and (c) 1 m/s.

Furthermore, the HTF velocity significantly impacted the development of boundary layers on the PCM surface. This led to increased mixing and agitation inside the PCM and changes in its effective thermal conductivity. All of these factors directly affected the velocity profiles of the PCM. The design and geometry of a system also influence the relationship between the velocities of a heat transfer fluid (HTF) and phase change material (PCM). These include factors such as flow constraints or turbulence caused by small passages or intricate shapes, which affect the shape of the velocity profiles. The linkages between fluid mechanics and heat transfer principles are of utmost importance in enhancing the performance of thermal energy storage systems and heat exchangers that involve interactions between phase change materials (PCMs) and heat transfer fluids (HTFs).

A captivating interaction between heat transmission and fluid dynamics characterizes PCM melting. At first, heat transfers from the source via the solid phase change material

(PCM), causing a thin layer near the hot surface to melt. Melting causes density variations that lead to natural convection. Less dense liquid PCM rises due to increased temperature, while denser, cooler liquid sinks, resulting in intricate flow patterns inside the domain. The melting front, the interface between solid and liquid states, changes continuously due to the combined effects of heat transmission and flow dynamics. A “mushy zone” with a combination of solid and liquid components adds complexity to the flow characteristics. The flow patterns are greatly influenced by the shape and orientation of the container, as well as by any present fins or heat transfer enhancers. Comprehending the complex relationship between thermal and fluidic processes is essential for enhancing PCM performance in various applications.

The flow of the molten PCM began in a narrow region next to the wall, progressively spreading in size and speed throughout the process. Significantly, velocities were considerably higher in regions close to the solid phase, where the most efficient heat transfer occurred. As mentioned before, the speed of the molten PCM was directly related to the speed of the HTF. The highest speeds measured were 0.13 mm/s, 0.17 mm/s, and 0.19 mm/s at HTF speeds of 0.01 m/s, 0.1 m/s, and 1 m/s, respectively. This observation highlights the impact of HTF velocity on the dynamics of PCM movement in a system, where higher HTF velocities enable bigger magnitudes of velocity within a molten PCM region.

Figure 7 represents how the amount of liquid in the phase change material (PCM) changed over time for different speeds of the heat transfer fluid (HTF). During the melting process, the amount of liquid steadily increased over time, and the melting rate rose proportionately to the heat transfer fluid’s velocity. The overall duration required for complete melting varied, with recorded values of 1700, 1800, and 1900 s for HTF velocities of 1 m/s, 0.1 m/s, and 0.01 m/s, respectively. In contrast, at the 1000 s mark, the achieved liquid fractions were 0.81, 0.78, and 0.76 for the respective HTF velocities. These data highlight the significant impact of HTF velocity on the rate of phase change within the PCM domain. Higher velocities of the heat transfer fluid (HTF) are directly associated with faster melting rates. This leads to shorter overall melting durations and increased amounts of liquid at equivalent time intervals. These findings reveal the critical role that HTF velocity plays in controlling the efficiency and timing of phase change processes in thermal energy storage systems and heat exchangers that involve interactions between PCMs and HTFs.

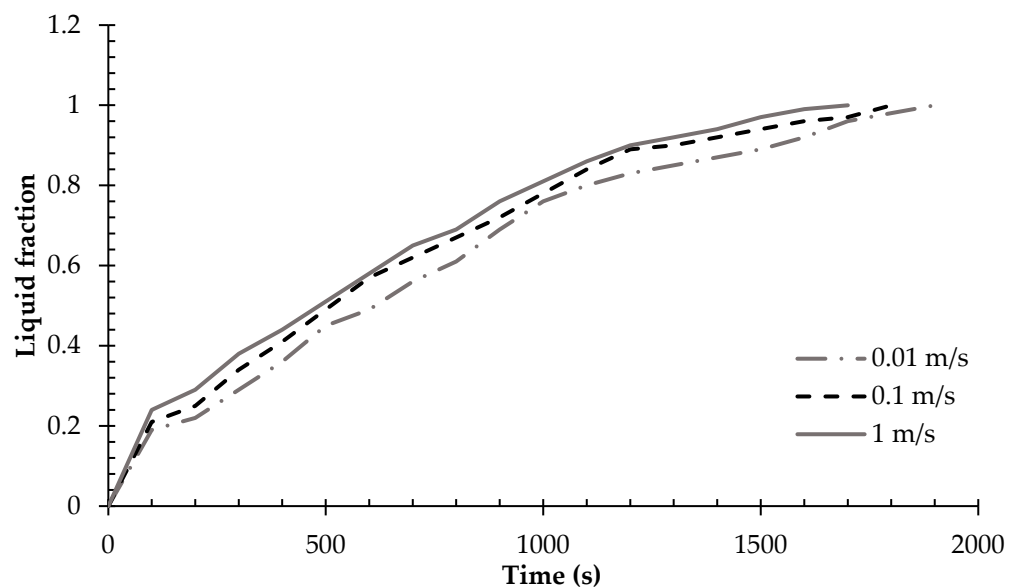


Figure 7. Liquid fraction for different velocities of the HTF.

Figure 8 presents the temperature profile at a singular point at the center of the phase change material (PCM) domain. Initially, the PCM maintained a consistent temperature

of 310 K, which persisted until 600 s into the heat exchange process. Subsequently, as heat was transferred to this point, the temperature significantly increased, primarily due to the convection process. Notably, the rate of temperature increase was observed to be faster with higher velocities of the heat transfer fluid (HTF). Specifically, at 900 s into the operation, temperatures of 326 K, 327.7 K, and 329.4 K were recorded for HTF velocities of 0.01 m/s, 0.1 m/s, and 1 m/s, respectively. This observed trend can be attributed to the enhanced heat transfer associated with higher HTF flow rates. Increased fluid velocity leads to more efficient convective heat transfer, resulting in a more rapid rise in temperature at the specified point within the PCM domain. Beyond 900 s, the heat exchange rate gradually diminished due to the decreasing temperature difference between the PCM and the HTF. Ultimately, at 1800 s, the temperature stabilized at 330 K and 333 K for the minimum and maximum HTF velocities, respectively. This comprehensive analysis underscores the significant influence of HTF velocity on temperature distribution and heat transfer dynamics within the PCM domain, highlighting the importance of fluid flow characteristics in optimizing thermal performance in phase change material systems. Finally, Figure 9 depicts an examination of the velocity of the molten phase change material (PCM) at the identical location studied in Figure 8. The movement of the PCM commenced at 600 s, aligning with the beginning of PCM liquefaction. Afterwards, the motion at this juncture experienced a sudden surge in speed due to the assimilation of convective heat, leading to a swift escalation in velocity until the 900 s mark. After this point, the movement gradually declined as the heat exchange rate lowered due to the decrease in temperature differences between the phase change material (PCM) and the heat transfer fluid (HTF). Ultimately, when the phase change material (PCM) temperature reached thermal equilibrium with the heat transfer fluid (HTF), the speed of the PCM lowered both at this specific spot and across the entire area. As the HTF velocity increased, the observed rise in PCM velocity could be attributed to the improved heat exchange facilitated by higher fluid velocities. This process is consistent with the principles of convective heat transfer, where higher fluid flow rates lead to more effective heat transmission. This, in turn, leads to increased momentum transfer and higher velocities of a phase change material (PCM). At the 900 s mark, the highest observed velocities were 0.2 mm/s and 0.15 mm/s for HTF velocities of 1 m/s and 0.01 m/s, respectively. This trend emphasizes the substantial influence of HTF velocity on PCM motion and emphasizes the interaction between fluid dynamics and heat transfer processes in the PCM domain.

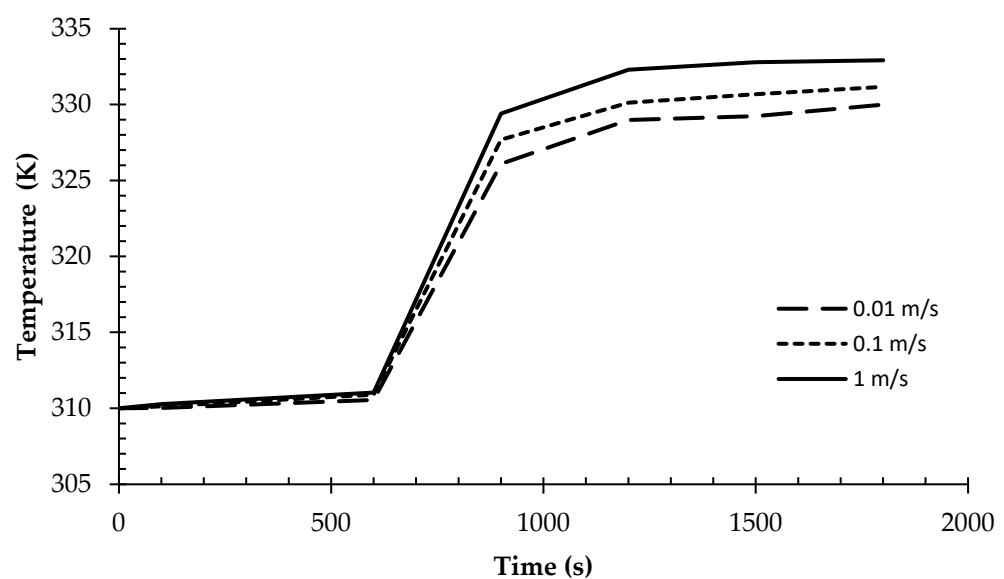


Figure 8. Temperature of the PCM for different velocities of the HTF.

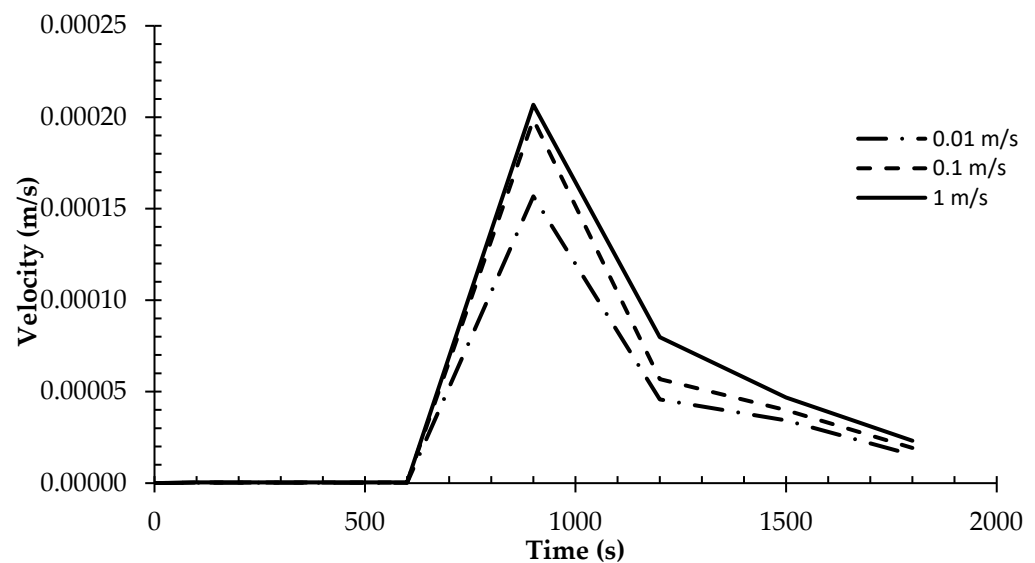


Figure 9. The velocity of the PCM for different velocities of the HTF.

5. Conclusions

This work used numerical techniques to examine how water velocity affects phase change material (PCM) melting in a vertical cylindrical container. A quantitative investigation was carried out to clarify the connection between enthalpy and porosity using the ANSYS/FLUENT 16 program. Rubitherm RT42, a paraffin wax-based substance exhibiting phase transitions, was used in this experiment. With a constant temperature of 333 K, the study investigated the effects of different water velocities, specifically at speeds of 0.01 m/s, 0.1 m/s, and 1 m/s. This work sought to understand the dynamics of the melting process, which has consequences for comprehending the thermal behavior of PCM systems under various flow circumstances. The main conclusions of this work are as follows:

1. The melting process initiates near the domain boundaries, with the solid PCM gradually transitioning to liquid state over time regardless of the heat transfer fluid (HTF) velocity.
2. Higher HTF velocities result in a more rapid increase in the liquid phase size and a corresponding decrease in the solid phase, indicating a faster melting process.
3. The upward movement of liquid PCM within the domain is primarily influenced by convective currents, buoyancy forces, and thermal gradients, rather than solely by density differences.
4. The density variations caused by melting solid PCM lead to natural convection, where less dense liquid rises due to increased temperature and denser, cooler liquid sinks.
5. Enhanced HTF velocities lead to faster melting rates and a decrease in the remaining solid phase, underscoring the importance of fluid dynamics in affecting phase change kinetics.
6. The velocity of molten PCM within the domain directly correlates with HTF speed, highlighting the significant impact of HTF velocity on PCM movement and the overall efficiency of phase change processes.

Future studies could examine how container geometries affect phase change material melting, how temperatures affect water velocity and PCM behavior, and how numerical simulations can be experimentally validated to improve accuracy and reliability. Further research could also optimize thermal energy storage system design parameters using PCM–HTF interactions, including material properties, flow dynamics, and heat transfer processes.

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Data curation, A.F.K., F.L.R., S.A.L., A.A. and H.I.M.; Writing—original draft preparation, A.F.K., F.L.R., S.A.L. and H.I.M.; Writing—review and editing, A.F.K., F.L.R. and A.A.; Visualization, A.F.K., F.L.R., S.A.L., A.A. and H.I.M.; Project administration, F.L.R. and A.A. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

C_p	specific heat capacity J/(kg·K)
k	thermal conductivity W/(m·K)
L	latent heat J/kg
T	temperature K
β	melting fraction
μ	dynamic viscosity kg/(m·s)
ρ	density kg/m ³

References

1. Mousavi Ajarostaghi, S.S.; Hosseinian-Sorkhi, A.; Arıcı, M. Influence of immiscible intermediate fluid on melting process in a horizontal shell-and-tube phase change material storage. *J. Therm. Anal. Calorim.* **2023**, *148*, 11013–11027. [\[CrossRef\]](#)
2. Bull, S.R. Renewable Energy Today and Tomorrow. *Proc. IEEE* **2001**, *89*, 1216–1226. [\[CrossRef\]](#)
3. Sharma, A.; Tyagi, V.V.; Chen, C.R.; Buddhi, D. Review on Thermal Energy Storage with Phase Change Materials and Applications. *Renew. Sustain. Energy Rev.* **2009**, *13*, 318–345. [\[CrossRef\]](#)
4. Younsi, Z.; Joulin, A.; Zalewski, L.; Lassue, S.; Rousse, D.R. Phase Change Materials: A Numerical Method for the Behavior Predictions. In Proceedings of the Fourth International Conference on Thermal Engineering: Theory and Applications, Abu Dhabi, United Arab Emirates, 12–14 January 2009; pp. 12–14.
5. Shokouhmand, H.; Kamkari, B. Experimental Investigation on Melting Heat Transfer Characteristics of Lauric Acid in a Rectangular Thermal Storage Unit. *Exp. Therm. Fluid. Sci.* **2013**, *50*, 201–212. [\[CrossRef\]](#)
6. Sun, X.; Chu, Y.; Mo, Y.; Fan, S.; Liao, S. Experimental Investigations on the Heat Transfer of Melting Phase Change Material (PCM). *Energy Procedia* **2018**, *152*, 186–191. [\[CrossRef\]](#)
7. Yadav, A.; Samir, S. Experimental and Numerical Investigation of Spatiotemporal Characteristics of Thermal Energy Storage System in a Rectangular Enclosure. *J. Energy Storage* **2019**, *21*, 405–417. [\[CrossRef\]](#)
8. Abderrahmane, A.; Qasem, N.A.A.; Mourad, A.; Al-Khaleel, M.; Said, Z.; Guedri, K.; Younis, O.; Marzouki, R. Enhancing the Melting Process of Shell-and-Tube PCM Thermal Energy Storage Unit Using Modified Tube Design. *Nanomaterials* **2022**, *12*, 3078. [\[CrossRef\]](#)
9. Alshara, A.K.; Kadhim, M.K. Numerical Investigation of Energy Storage in Packed Bed of Cylindrical Capsules of PCM. *Eng. Technol. J.* **2014**, *32*, 494–510. [\[CrossRef\]](#)
10. Hlimi, M.; Hamdaoui, S.; Mahdaoui, M.; Kousksou, T.; Ait Msaad, A.; Jamil, A.; El Bouardi, A. Melting inside a Horizontal Cylindrical Capsule. *Case Stud. Therm. Eng.* **2016**, *8*, 359–369. [\[CrossRef\]](#)
11. Bechiri, M.; Mansouri, K. Study of Heat and Fluid Flow during Melting of PCM inside Vertical Cylindrical Tube. *Int. J. Therm. Sci.* **2019**, *135*, 235–246. [\[CrossRef\]](#)
12. Al-Mudhafar, A.H.N.; Tarish, A.L. Enhancing PCM melting in a triple tube heat exchanger by utilizing innovative fins configurations. *J. Braz. Soc. Mech. Sci. Eng.* **2024**, *46*, 262. [\[CrossRef\]](#)
13. Soodmand, A.M.; Azimi, B.; Nejatbakhsh, S.; Pourpasha, H.; Farshchi, M.E.; Aghdasinia, H.; Mohammadpourfard, M.; Heris, S.Z. A comprehensive review of computational fluid dynamics simulation studies in phase change materials: Applications, materials, and geometries. *J. Therm. Anal. Calorim.* **2023**, *148*, 10595–10644. [\[CrossRef\]](#)
14. Rizan, M.Z.M.; Tan, F.L.; Tso, C.P. An Experimental Study of N-Octadecane Melting inside a Sphere Subjected to Constant Heat Rate at Surface. *Int. Commun. Heat. Mass. Transf.* **2012**, *39*, 1624–1630. [\[CrossRef\]](#)
15. Ismail, K.A.R.; Moura, L.F.; Lago, T.; Lino, F.A.M.; Nobrega, C. Experimental Study of Fusion and Solidification of Phase Change Material (PCM) in Spherical Geometry. In Proceedings of the 12th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Costa de Sol, Spain, 11–13 July 2016; pp. 1243–1248.
16. Sattari, H.; Mohebbi, A.; Afsahi, M.M.; Azimi Yancheshme, A. CFD Simulation of Melting Process of Phase Change Materials (PCMs) in a Spherical Capsule. *Int. J. Refrig.* **2017**, *73*, 209–218. [\[CrossRef\]](#)

17. Agarwal, A.; Sarviya, R.M. An Experimental Investigation of Shell and Tube Latent Heat Storage for Solar Dryer Using Paraffin Wax as Heat Storage Material. *Eng. Sci. Technol. Int. J.* **2016**, *19*, 619–631. [\[CrossRef\]](#)
18. Fahmy, M.; Morsy, M.; Abd Elshakour, H.; Belal, A.M. Effect of Thermal Insulation on Building Thermal Comfort and Energy Consumption in Egypt. *J. Adv. Res. Appl. Mech.* **2018**, *43*, 8–19.
19. Izadi, M.; Saleem, A.; Alshehri, H.M.; Ambreen, T.; Yasuri, A.K. Influence of Geometric Parameters on the Charging process of PCM in Semi-circular thermal storages for energy management. *Environ. Sci. Pollut. Res.* **2023**, *30*, 59765–59780. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Esapour, M.; Hosseini, M.J.; Ranjbar, A.A.; Pahamli, Y.; Bahrampoury, R. Phase Change in Multi-Tube Heat Exchangers. *Renew. Energy* **2016**, *85*, 1017–1025. [\[CrossRef\]](#)
21. Ebrahimi, A.; Hosseini, M.J.; Ranjbar, A.A.; Rahimi, M.; Bahrampoury, R. Melting Process Investigation of Phase Change Materials in a Shell and Tube Heat Exchanger Enhanced with Heat Pipe. *Renew. Energy* **2019**, *138*, 378–394. [\[CrossRef\]](#)
22. Khalaf, A.F.; Rashid, F.L.; Basem, A.; Abbas, M.H. Numerical analysis in a lid-driven square cavity with hemispherical obstacle in the bottom. *Math. Model. Eng. Probl.* **2022**, *9*, 1639–1647. [\[CrossRef\]](#)
23. Jesumathy, S.; Udayakumar, M.; Suresh, S. Experimental Study of Enhanced Heat Transfer by Addition of CuO Nanoparticle. *Heat. Mass. Transf.* **2012**, *48*, 965–978. [\[CrossRef\]](#)
24. Harikrishnan, S.; Kalaiselvam, S. Preparation and Thermal Characteristics of CuO–Oleic Acid Nanofluids as a Phase Change Material. *Thermochim. Acta* **2012**, *533*, 46–55. [\[CrossRef\]](#)
25. Rashid, F.L.; Basem, A.; Khalaf, F.A.A.; Abbas, M.H.; Hashim, A. Recent Breakthroughs and Improvements in Phase Change Material Melting in a Triple-Tube Thermal Storage Unit. *Rev. Compos. Mater. Av.* **2022**, *32*, 295. [\[CrossRef\]](#)
26. Tiji, M.E.; Al-Azzawi, W.K.; Mohammed, H.I.; Dulaimi, A.; Rashid, F.L.; Mahdi, J.M.; Majdi, H.S.; Talebizadehsardari, P.; Ali, H.M. Thermal Management of the Melting Process in a Latent Heat Triplex Tube Storage System Using Different Configurations of Frustum Tubes. *J. Nanomater.* **2022**, *2022*, 7398110. [\[CrossRef\]](#)
27. Uniyal, A.; Prajapati, Y.K. Impact of Fin Arrangement on Heat Transfer and Melting Characteristics of Phase Change Material. *J. Therm. Sci.* **2024**, *33*, 435. [\[CrossRef\]](#)
28. Kong, D.; Zhang, Y.; Liu, S. Enhanced Natural Convection for Accelerating Melting of Phase Change Material in Cellular Structure through Inserting Fin. *J. Therm. Sci.* **2024**, *33*, 548. [\[CrossRef\]](#)
29. Mao, Q.; Zhu, Y.; Li, T. Heat Storage Performance of PCM in a Novel Vertical Pointer-Shaped Finned Latent Heat Tank. *J. Therm. Sci.* **2024**, *33*, 422. [\[CrossRef\]](#)

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